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PRECISE STATION COORDINATE DETERMINATION FROM DORIS TRACKING OF THE TOPEX/POSEIDON SATELLITE

M. M. Watkins*, G. W. Davis* and J. C. Ries*

The French DORIS doppler satellite tracking/positioning system has been tracking the TOPEX/Poseidon oceanographic satellite since August 16, 1992. To date, 270 days of DORIS data from 50 ground beacons have been analyzed to determine three dimensional site coordinates, a subset of which agree with positions determined from the established techniques of laser ranging and radio interferometry at the 10-20 millimeter level in each coordinate after removal of common rotations, translations and a scale difference. The translation parameters indicate that the DORIS network realizes a geocentric frame to 20-50 mm in each component. These results show a marked improvement over a similar study using 80 days of DORIS data from the SPOT-2 satellite, which was anticipated because of the greater data span, reduced magnitude of the gravitational and drag perturbations acting on the higher altitude TOPEX/Poseidon spacecraft and because of the improved gravity model used in the orbit determination process.

INTRODUCTION

The use of space-based observation systems to precisely monitor earth and ocean processes that produce small changes over large temporal and geographic scales, e.g., mean sea level change or plate tectonics, relies heavily upon the ability of the satellite tracking system to provide global station coordinates with centimeter-level accuracy in a geocentric frame. Currently, there exists three such high quality, multisite satellite tracking and positioning systems : satellite laser ranging (SLR), the Global Positioning System (GPS), and the Determination d'Orbite et Radiopositionnement Integres par Satellite (DORIS) tracking system. Very long baseline interferometry (VLBI), is capable of providing outstanding relative site positions, and hence implied plate motions, but the frame is oriented arbitrarily in translation, that is, it is not tied to the center of mass of the Earth. While SLR has been the most successful of the satellite techniques to date, having demonstrated the capability of determining site positions with subcentimeter accuracy and site velocities with few millimeter per year accuracy [Ray et al., 1991; Himwich et al., 1992; Watkins et al., 1992a], GPS [Blewitt et al., 1992] and DORIS [Cazenave et al., 1992; Watkins et al., 1992b] have also demonstrated exceptional accuracy. The DORIS tracking system was designed and developed since 1982 by the Centre National d'Etudes Spatiale (CNES), the Institut Geographic National (IGN) and the Groupe de Recherche de Geodesie Spatiale (GRGS) in a collaborative effort to support 10 cm level radial orbit determination for low Earth satellites, particularly the Topex/Poseidon (T/P) mission [Nouel et al., 1988]. Watkins et al., [1992b], demonstrated the DORIS absolute positioning capability using three months of data taken on SPOT-2 during the so-called

* Center for Space Research, The University of Texas at Austin, Code 60605, Austin, Texas 78712-1085.

Asymptotic Campaign in early 1992. It was shown that nine DORIS beacons collocated with SLR/VLBI sites agreed at the 25 mm rms level [Watkins et al., 1992b] after the removal of common rotations, translations, and a scale difference. Such results are quite impressive, considering the large perturbations due to atmospheric drag and to high frequency gravity effects that result from the low altitude of the SPOT-2 satellite. Accordingly, improvements in the DORIS ground beacon position determinations have been obtained with tracking data from the T/P oceanographic satellite, which is almost 600 km higher in altitude. This paper discusses the results derived from 270 days of DORIS data taken on T/P for the positioning of 50 ground beacons, including comparisons to SLR/VLBI positions for those sites where survey ties are available.

THE DORIS SYSTEM

The DORIS radiometric satellite tracking/positioning system has been tracking the TOPEX/Poseidon oceanographic satellite since August 16, 1992. DORIS is a one-way, ascending doppler system which utilizes a set of ground orbit beacons that broadcast continuously and omnidirectionally on two frequencies of 2036.25 and 401.25 Mhz. Each beacon contains an ultrastable quartz oscillator, with a stability on the order of 5×10^{-13} for periods of 10 to 100 seconds, as well as sensors for monitoring the temperature, pressure and humidity. The broadcast message, which is transmitted every 10 seconds, consists of the meteorological data, the beacon ID and a beacon status report. A space segment on-board the satellite receives the dual frequency ground transmissions with an omnidirectional antenna and using a ultrastable quartz oscillator similar to those at the beacon sites computes the doppler shift from which the average range-rate of the satellite is inferred. The space segment can process only one beacon at a time so it must be programmed in advance to multiplex the signals from several commonly viewed beacons. The global distribution of the DORIS tracking sites is shown in Fig. 1. The nearly isotropic distribution of beacons coupled with the high data rate of one measurement every 10 seconds enables the DORIS system to provide both a spatially and temporally dense set of tracking data.

THE TOPEX/POSEIDON SATELLITE

The TOPEX/Poseidon satellite carries both a dual frequency radar altimeter developed by NASA and a single frequency solid-state altimeter developed by CNES to map the ocean surface for a period of 3-5 years. Additional information on the T/P satellite and its instrumentation is found in Tapley et al., 1990. T/P was launched on August 10, 1992 and occupies a 66 degree inclination orbit with an altitude of 1330 km and an eccentricity of 0.0004. The repeat period is 9.915625 days. Because of the high altitude, perturbations due to higher degree and order terms in the Earth's gravitational field and due to atmospheric drag on the spacecraft orbit are attenuated; however, perturbations due to solar radiation pressure at this altitude are significant [Ries et al., 1992].

DATA SET

To date, 27 repeat cycles of T/P DORIS data have been analyzed. The DORIS tracking system routinely collects about 100 passes per day, with occasional data gaps and days with weak tracking due primarily to hardware upsets resulting from high radiation levels or due to problems associated with the DORIS master beacon's ability to upload the daily work program. The passes per station as a function of increasing latitude and longitude are shown in

Fig. 2. Note the large latitude range, with SYOB (Syowa Base, Antarctica) at -69 degrees South latitude and SPIA (Spitzbergen, Norway) at 79 degrees North latitude. It is seen that the data distribution is biased toward the poles, with a slight slightly greater amount collected in the southern hemisphere. It is also seen that the data is fairly well distributed longitudinally.

Preliminary orbits were fit to the data on a cycle-by-cycle basis to allow editing of the observations using the Guier plane editing algorithm [Guier and Newton, 1965; Anderle, 1973], which resulted in a loss of approximately 1-2 % of the data. The majority of passes eliminated in the editing procedure were rejected because the passes were very short or had large gaps, or because the estimated noise level of the passes exceeded 1 mm/sec. The average estimated precision of the data was 0.51 mm/sec, based upon removing systematic signals in each pass through the estimation of a troposphere correction, frequency offset, and slant range and tangential orbit corrections. For the station solutions, additional passes were deleted when it was judged that there was insufficient data in a particular daily or 8-hour arc to support the estimation of the numerous parameters required to extract precise doppler orbits. Similarly, arcs that spanned satellite attitude maneuvers such as safeholds, yaw flips and orbital altitude increases were also deleted. The final data set thus consisted of 1288897 observations in 28587 passes (14360 ascending, 14227 descending) from 50 beacons. Table 1 lists the beacons, their locations, and the amount and precision of the data collected. An asterisk following the location indicates that the beacon has a survey tie to an SLR or VLBI site.

ORBIT ANALYSIS

The data were processed in the University of Texas orbit determination package UTOPIA, which incorporates models for the Earth's gravitational field, solid Earth and ocean tides, atmospheric drag, Earth radiation pressure, relativity and n-body perturbations from the Sun, Moon and planets. The gravitational field used was the TOPEX/Poseidon post-launch model, JGM-2, which contains T/P SLR and DORIS data. This field was produced jointly by the NASA Goddard Spaceflight Center, the University of Texas Center for Space Research, and CNES. The measurement model used the dual frequency derived ionospheric correction, relativistic corrections and a tropospheric zenith delay was adjusted for each pass using the modified Hopfield mapping function. The satellite dynamic and measurement models include algorithms for yaw-steering of the satellite and for pitching of the solar panel array to allow accurate orbit modeling and computation of center of mass location.

To assess the effects of orbit errors on the site positions, several orbital parameterizations and arc lengths were studied. The longest arc used was 9.9 days, the length of a T/P repeat cycle, and the shortest arc used was eight hours. Long arcs provide dynamical constraints through the satellite equations of motion while short arcs tend to attenuate long-period and resonant gravity errors and reduce the build-up of non-conservative surface force models errors. For each arc length used, the drag force and radiation pressure forces were held constant at nominal values, while along track accelerations (Ct) and empirical transverse (T) and normal (N) accelerations, which vary around each revolution with argument of latitude, were adjusted for various sub-arc lengths. Also, nominal accelerations along the satellite body-fixed x and y axes were included to account for anomalous surface forces possibly due to thermal radiation effects and outgassing.

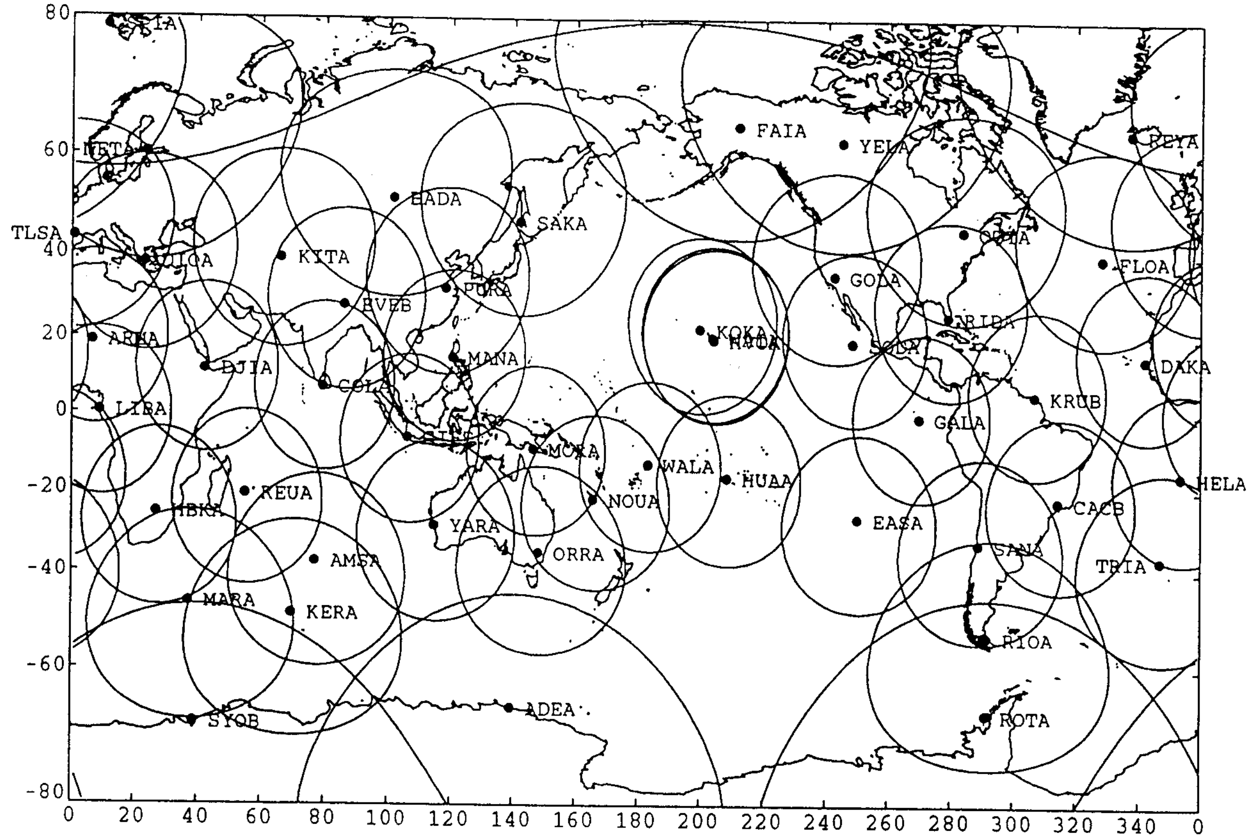

Fig. 1 DORIS Stations Tracking TOPEX/Poseidon
15 Degree Elevation Masks

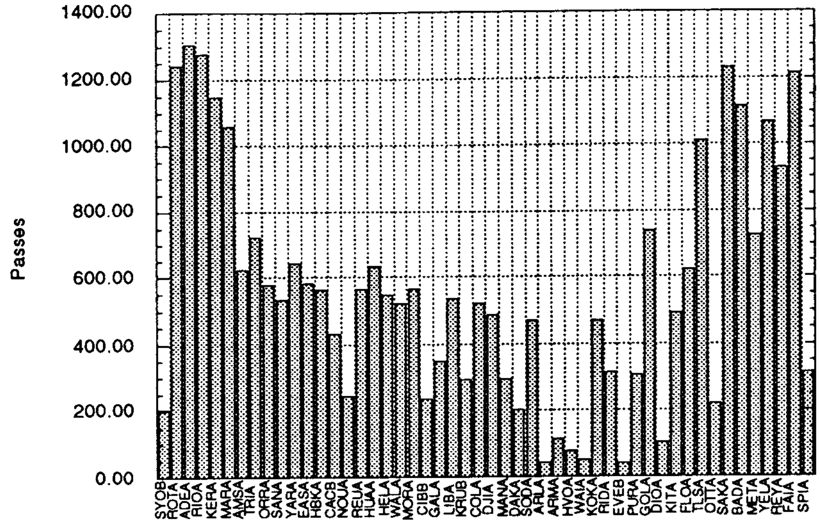

Fig. 2a Passes per Station (latitude increasing)

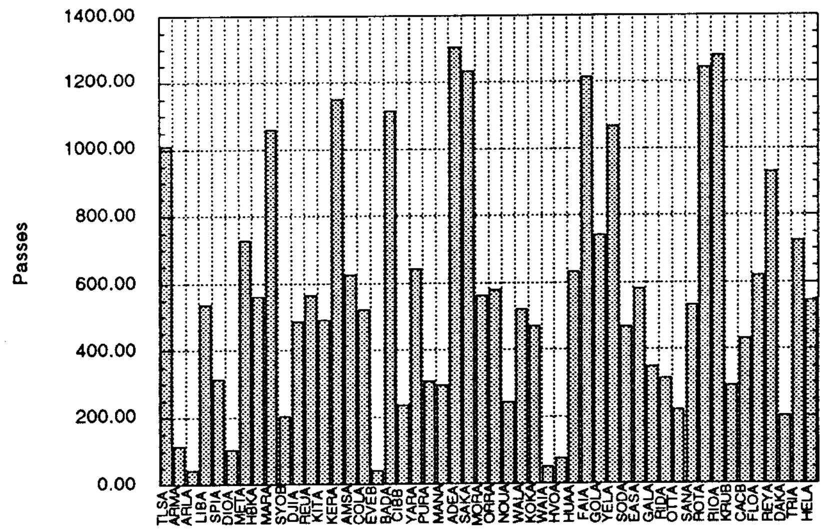

Fig 2b. Passes per Station (longitude increasing)

Table 1
TOPEX DORIS DATA IN STATION SOLUTION

Station ID		Station Location	# of Passes	# of Obs	Raw RMS cm/sec	Guier RMS cm/sec
4002	TLSA	Toulouse, France	1011	31318	0.060	0.054
4005	TRIA	Tristan Da Cunha Island	723	37108	0.052	0.047
4006	META	Metsahovi, Finland	727	28321	0.044	0.040
4008	AMSA	Amsterdam Island, Netherlands	624	24527	0.052	0.048
4009	KERA	Kerguelen Island	1149	43723	0.061	0.056
4010	GOLA	Goldstone, California *	742	25956	0.054	0.050
4012	REUA	La Reunion Island	565	25459	0.051	0.047
4013	LIBA	Libreville, Gabon	536	22741	0.053	0.049
4017	RIOA	Rio Grande, Argentina	1279	46540	0.057	0.053
4018	DAKA	Dakar, Senegal	202	8947	0.047	0.044
4019	HBKA	Hartebeesthoek,South Africa *	562	23966	0.057	0.054
4020	SPIA	Spitzbergen, Norway	314	7235	0.054	0.051
4022	MARA	Marion Island	1059	42396	0.052	0.048
4025	DJIA	Djibouti, Somalia	487	17398	0.055	0.050
4027	HUAA	Huahine Island *	632	34957	0.052	0.050
4035	ARLA	Arlit, Niger	43	992	0.052	0.048
4036	NOUA	Noumea, New Caledonia	244	9144	0.055	0.052
4037	WALA	Wallis Islands	522	26262	0.078	0.075
4038	SANA	Santiago, Chile	535	21519	0.071	0.067
4041	EASA	Easter Island *	582	35898	0.055	0.051
4042	ADEA	Terre Adelie, Antarctica	1307	84468	0.050	0.047
4043	HELA	Sainte Helene Island	546	22056	0.059	0.055
4045	PURA	Purple Mountain, China	308	12293	0.100	0.086
4047	DIOA	Dionysos, Greece *	104	3551	0.052	0.048
4048	OTTA	Ottawa, Canada	221	11803	0.081	0.067
4051	YELA	Yellowknife, Canada *	1067	45949	0.053	0.049
4053	FLOA	Flores Island, Azores	622	26829	0.051	0.048
4055	MORA	Port Moresby, Papua New Guinea	564	30202	0.058	0.054
4201	REYA	Reykjavik, Iceland	929	39081	0.047	0.044
4202	FAIA	Fairbanks, Alaska *	1214	62303	0.049	0.046
4203	SAKA	Sakhalinsk, C.I.S.	1233	63722	0.050	0.048
4204	MANA	Manilla, Phillipines	294	11792	0.066	0.062
4205	BADA	Badary, C.I.S.	1115	56999	0.048	0.045
4206	COLA	Colombo, Sri Lanka	521	28032	0.050	0.047
4207	KOKA	Kauai, Hawaii *	470	26869	0.052	0.048
4208	KITA	Kitab, C.I.S.	492	24818	0.045	0.042
4209	HVOA	Hawaiian Volcano Observatory	77	937	0.062	0.053
4210	GALA	Galapagos Islands	349	15689	0.053	0.049
4211	ROTA	Rothera, Antarctica	1242	52936	0.056	0.052
4212	SODA	Socorro Island, Mexico	468	20834	0.054	0.051
4213	KRUB	Kourou, French Guiana	292	19940	0.063	0.058
4214	CACB	Cachoeira Paulista, Brazil	431	18991	0.046	0.040
4215	EVEB	Mt. Everest, Nepal	40	1333	0.066	0.062
4216	CIBB	Cibonong, Indonesia	236	10232	0.054	0.047
4217	ORRA	Orroral, Australia *	580	24674	0.056	0.052
4218	YARA	Yaragadee, Australia *	642	29632	0.046	0.043
4219	WAIA	Waimea, Hawaii	51	589	0.068	0.055
4220	ARMA	Arlit, Niger (new occupation)	114	2987	0.055	0.052
4221	RIDA	Richmond, Florida (new occ.)	315	15492	0.051	0.047
4222	SYOB	Syowa, Antarctica	205	9457	0.045	0.040

SITE COMPARISONS

In all cases, the sites positions determined from the T/P DORIS data were compared to the LAGEOS derived SSC(CSR)93L01 site positions of Eanes and Watkins [1992] after translation to common markers through the use of the ties in Table 2. In addition, to allow comparisons for VLBI sites with no SLR tie, the positions derived by the Goddard Space Flight Center VLBI analysis group, GLB886a, were mapped to epoch 1992.2 and transformed into the CSR93L01 frame using the 10 best sites for which those solutions have collocated solutions. This procedure added the sites at Fairbanks, Hartebeesthoek, Mojave, and Kokee Park. The large uncertainties associated with some of the ties result from the location of the DORIS beacons at considerable distances from the VLBI sites to reduce radio frequency interference. Since these ties are typically on the order of 1 kilometer, they are probably accurate to no more than a few centimeters; furthermore, since no uncertainties were reported with the ties, they were assigned an uncertainty of 1 m.

Table 2
SURVEY TIES FROM DORIS REFERENCE POINT TO MARKER

DORIS		SLR/ VLBI	Offset (m)			Uncertainty		
CNES NAME	CSR ID	CDP ID	X	Y	Z	σX	σY	σZ
DIOA	4047	7515	1.226	-40.030	14.416	0.01	0.01	0.01
GOLA	4010	7222	332.804	-171.8762	17.4136	0.01	0.01	0.01
KOKA	4207	1311	128.5870	26.2680	325.949	0.01	0.01	0.01
EASA	4041	7097	9.956	-3.329	5.267	0.01	0.01	0.01
HUAA	4027	7123	6.282	-7.965	0.173	0.01	0.01	0.01
HBKA	4019	7232	801.313	-2086.153	-199.887	1.0	1.0	1.0
YARA	4218	7090	-2.990	-11.270	-11.823	0.01	0.01	0.01
ORRA	4217	7843	-6.411	25.040	22.873	0.01	0.01	0.01
FAIA	4202	7225	955.8	-227.9	298.7	1.0	1.0	1.0

An additional comparison that was made for each case was the difference between the two sites at Arlit, Niger. After the removal of the original beacon, a second beacon was installed at a nearby location and the offset between the two surveyed with conventional techniques. The ARMA/ARLA baseline computed from the site determinations was compared with this survey tie provided by the IGN. The cartesian components of this tie were reported as 1362.703 m, 2163.733 m and -4825.938 m, respectively. Since the sites at ARLA and ARMA are different occupations with no overlap, they did not observe T/P simultaneously and thus the computed baseline will be corrupted by error sources that vary with time, such as the variable portion of tropospheric and the ionospheric refraction, drag and radiation pressure, and clock error. However, biases that are static such as gravity model induced geographically correlated orbit error and errors in constants such as GM of the Earth will be removed. Thus, the ARMA/ARLA baseline recovered from the site determinations provides a rough estimate on the DORIS relative positioning capabilities for short baselines, although the poor tracking by the original ARLA beacon (43 passes total) weakens the comparison considerably.

The DORIS coordinates were mapped from the nominal solution epoch of 1988.0 using a plate motion model based on the CSR93L01 velocity model for colocated sites and the Nuvel-1 model for other sites. The coordinate system was defined by fixing the longitude of the equatorial site at Libreville, Gabon to the nominal SPOT-2 derived value. All other coordinates were adjusted without constraint. For each comparison, a conventional 7-parameter Helmert transformation was removed from the coordinate differences, and the residuals presented in both cartesian and geodetic coordinates. Full intrasite correlations were included for both the DORIS coordinates and the SLR/VLBI set in order to transform the covariance into the geodetic system. The geodetic coordinates are particularly useful in identifying sources of error in the vertical direction, such as residual troposphere error, and in the north direction, which will be affected mostly by along-track errors due to the 66 degree inclination of T/P.

RESULTS

While many different combinations of arc lengths and parameterizations were investigated, only the results of the most interesting site determinations are presented in Table 3. Case 0 is the best of the solutions obtained from the SPOT-2 data [Watkins, et al., 1992]. In case 1, the arc length was 9.9 days and the sub-arc length for Ct and once-per-revolution T and N was 1 day and 3.3 days, respectively. Case 2 uses the same parameterization as case 1 but a subset of gravitational field Stokes' coefficients - two even and two odd degree for order 1, beginning at degree 3. In case 3, both the arc length and the sub-arc length was reduced to 1 day. Case 4 used the same arc length as case 3 while the subset of gravitational field Stokes' coefficients was expanded to two even and two odd degrees for orders 3-27, plus order 38. Cases 5,6 follow this same trend, with an arc length of 8 hours, except that in these short arcs the once-per-revolution N parameter was not adjusted. This is justified on the assumption that the radiation pressure force, which manifest itself predominantly as a force normal to the orbit plane, can not build up appreciably in such short arcs and is absorbed into the initial conditions. Cases 7 and 8 are the same as cases 5 and 6 except that the troposphere scaling parameter was constrained at the reasonable level of 5% uncertainty. Case 9 is the same as case 8 except that the stations were weighted according to the empirically estimated beacon internal precision. In cases 10 and 11, gravity coefficients were not adjusted but T/P laser ranging data was processed to provide radial orbit control and to provide sensitivity to the geocenter.

From Table 3, it is observed that DORIS data obtained from T/P and processed in 9.9 day arcs yields better positioning results than those obtained from SPOT-2, which required 8 hour arcs and the adjustment of gravity coefficients. This is significant only in that the use of 9.9 day arcs is much more efficient than 8 hour arcs in terms of computation time and effort spent by the orbit analyst in editing and preparing the data. Table 3 also reveals that reducing the arc length and sub-arc length results in better site determinations and also strengthens the ability of the DORIS system to realize a geocentric reference frame. Another trend that is apparent is that the estimation of gravity coefficients tends to worsen the positioning results for a particular arc length, but improves the geocenter realization. This is likely attributable to the high quality of the JGM-2 gravity field, with the remaining errors difficult to separate from other orbital effects and the residual errors in the DORIS system. It is also observed that as the arc length is decreased, the agreement between the computed ARMA/ARLA baseline and the tie provided by the IGN seems to decrease unless the troposphere scaling parameter is constrained. This may be due to the low elevation tracking by the original Arlit site which benefits by additional a priori information to separate orbit error from troposphere. Since the baseline differences were always long compared with the survey, the possibility of a bias in that value is suspected, although we note that the formal uncertainty, scaled to yield site coordinate uncertainties consistent with the comparison above yield an uncertainty on the Arlit baseline difference on the order of 100 mm due to the weak tracking by the original ARLA beacon.

Table 4 provides the site by site residuals for the Case 7, which yielded the best relative positioning as defined by agreement with the SLR/VLBI coordinates. The only significantly large residuals are those at Fairbanks, for which the tie was only reported to significant digits at the 100 mm level, and is consequently downweighted. It is interesting to point out that the 17 mm overall rms agreement with the SLR/VLBI coordinates is the same as that found by Blewitt et al. [1992] in their analysis of global GPS site positions.

CONCLUSIONS

Improved positioning using global DORIS tracking of the Topex/Poseidon satellite has been demonstrated using the first 27 cycles of data. The best parameterization, 8 hour adjustments of initial conditions, an empirical once-per-revolution transverse acceleration and an along-track acceleration, yields an adjusted network which agrees with a set of 9 colocated SLR and VLBI sites to 17 mm overall rms. Since many of the DORIS beacons are located in regions of high geophysical interest with little historical data from other high quality positioning techniques, continued performance at the current level will certainly yield interesting scientific returns in the years to come.

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Table 3
SITE DETERMINATION RESULTS

Case	Arc Length (days)	Parameters adjusted [1]	ΔE	ΔN	ΔU	3D RMS	DX	DY	DZ	Arlit Tie
All units are millimeters										
0	0.33	ic,Cd,R,g	38	20	16	26	-4	52	39	-----
1	9.9	ic,Ct,TN	30	16	21	23	-63	-09	-33	-95
2	9.9	ic,Ct,TN,g	34	16	23	25	-23	12	-36	-97
3	1.0	ic,Ct,TN	29	17	18	22	-58	-12	-39	-100
4	1.0	ic,Ct,TN,g	30	19	18	23	-17	13	40	-103
5	0.33	ic,Ct,T	16	24	17	19	-20	14	-54	-146
6	0.33	ic,Ct,T,g	38	25	18	28	-24	17	33	-146
7	0.33	ic,Ct,T [2]	15	22	15	17	-18	11	57	-64
8	0.33	ic,Ct,T,g [2]	25	21	16	21	-17	13	-45	-62
9	0.33	ic,Ct,T,g [2,3]	13	17	32	22	-34	31	-20	-132
10	0.33	ic,Ct,T [2,4]	15	19	18	17	-22	21	-34	-61
11	0.33	ic,Ct,T [2,5]	16	20	19	18	-34	22	-27	-61

1 - ic = initial conditions, Cd=drag scaling parameter, Ct=along-track acceleration, R=once-per-rev radial acceleration, T=once-per-rev transverse acceleration, N=once-per-rev radial acceleration, g=subset of gravity coefficients
2 - troposphere scaling parameter constrained at 5%
3 - stations weighted according to Guier rms
4 - SLR data processed, SLR stations adjusted
5 - SLR data processed, SLR stations not adjusted

Table 4
SITE COMPARISON FOR CASE 7

Sites		Differences After Fit (mm)					
DORIS	SLR/VLBI	X	Y	Z	East	North	Vert.
4010	7222	10	-2	-23	10	-17	-16
4019	7232	-42	-52	64	-27	30	-83
4027	7123	26	-6	-16	18	-21	-14
4041	7097	-2	-37	30	11	43	18
4047	7515	29	37	132	22	78	115
4051	7225	-68	-143	-55	84	-145	7
4217	7843	-10	19	-11	-11	2	21
4218	7090	-1	0	24	1	22	-12
4207	1311	-11	24	5	-27	4	4
Weighted RMS		14	19	20	15	22	15

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